AMIRKABIR NATM TUNNEL- A CASE STUDY OF DESIGN CHALLENGES IN A MEGA PROJECT OF TUNNEL IN SOFT GROUND

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ABSTRACT

In spite of enhancement in modeling techniques as well as site investigation methods, uncertainty exists seriously in the process of construction of underground structure in soft soils. These uncertainties arise from limited data of geological data, measurement errors, interpolation of spatially geological properties, and extrapolation of results of experiments and natural analogue studies over times and conditions relevant to the project. Robust and optimize design of tunnel support pattern consists many important parameters including advance rate and excavation method. However, quantitative definition of these parameters is difficult because of restricting in site investigation data and uncertainties related to them. Furthermore, erroneous evaluation in these parameters can affect in incorrect projection of tunnel stability or economic loss.

The work reported in this paper specifically dealt withAmirkabir highway tunnel with approximately 1.5Km long in eachtube (i.e.,north and southtubes).It is one of the important projects excavating below one of the highest traffic region of Tehran, including the difficulty of excavating through a heterogeneous sedimentary basin mainly composed of recent alluvial. Construction has been performed by different methods i.e., Underground excavation, Cut and Cover and Top/Down methods in different sections of the project. Deformations and settlements have been monitored during and after construction in order to avoid unpredictable deformations and as a result any possible failure.

Similar to other part of the project, a probabilistic hypothetical elasticity modulus (PHEM) approach has been employed to evaluate the uncertainty in lining design of a horseshoe shape NATM(New Austrian Tunneling Method) tunnel in T4 section of the project.The hybrid model, PHEM, consisting two essential parts is used to evaluate the performance of the system. A MATLAB interface program for generating the ABAQUS-based parametric model in one hand; and a Monte Carlo algorithm (Latin Hyper Cube Sampling method) to simulate the uncertainty existed in the system on the other hand are applied to produce the probabilistic density function of surface settlement of tunnel excavation and lining phases. In comparison with the monitoring data, the numerical results show that the PHEM approach introduced has had an appropriate prediction in surface settlements, improved the classical deterministic approaches.

Key Words:probabilistic hypothetical elasticity modulus approach, NATM Tunneling, uncertainty management, reliability analysis

INTRODUCTION

In spite of enhancement in modeling techniques as well as site investigation methods (to predict the settlements induced), uncertainty seriously exists in the process of construction of underground structures in soft soils.

These uncertainties arise from limited geological data, measurement errors, interpolation of spatially geological properties, and extrapolation of experimental results and natural analogue studies over times and conditions relevant to the project(You et al. 2005). Robust and optimize design of tunnel supports pattern consists of many important parameters including advanced rate and excavation method. However, quantitative definition of these parameters is difficult because of restricting in site investigation data and uncertainties related to them.

Furthermore, erroneous evaluation in these parameters can affect in incorrect projection of tunnel stability or economic loss(You et al. 2005). Meanwhile, the probabilistic (or reliability) approach, as a more reasonable and realistic treatment for the uncertainties, has been invoked to achieve current requirements in many fields of geotechnics these years(Su et al. 2011).A probabilistic approach, when it is possible to have sufficient data on the quality of the material, leads to better understanding of the project risks;more efficient geomechanical zoning; and a more reliable estimation of the costs(Oreste 2005).

The work reported in this paper specifically dealt withAmirkabirhighway tunnelexcavating below one of thehighest population density and traffic region of Tehran (Fig 1).

Fig 1 Location of Amirkabir project

Using different methods of excavation to avoid worse case settlement in different part, a probabilistic approach, Monte Carlo simulation algorithm (Latin Hyper Cube sampling), has been employed to evaluate the uncertainty in lining design of the part T4 of the project.

For better understanding the difficulties in design challenges faced in varioussubdivisions of the project, the next section deal with the overview of the whole project, continuing with different method of excavation methods and at last it has been reported that how turning to a probabilistic method in design could help in predicting the excavation-induced transversal settlement.

PROJECT OVERVIEW

Amirkabir tunnel with approximately 1.5Km long in each line (north and south) is located between 17 Shahrivar Street and Imam Ali highway. In Kerman square, the tunnel is divided into two branches. The north branch is located under Doroodian Street and the south branch is located under Kerman Street. Figures 2 shows plan of different sectionsof Amirkabir project.

Geology and Material Characteristic of The Site

The study area is located on sedimentary basin mainly composed of recent alluvial. Based on stratigraphical properties of the site, these sediments were categorized intofour different series namely A, B, C and D.

A is the oldest deposits and D is the youngest. Conglomerates with interbeded layers such as Sandstone, Siltstone and Mudstone composed A formation.

On the contrary, B formation is a heterogeneous unit with low sorting of grains; and C is mainly from recent alluvial fan composed of homogenous conglomerate.

This unit is stiffer than both of B and D formations, the youngest unit made of recent alluvial.

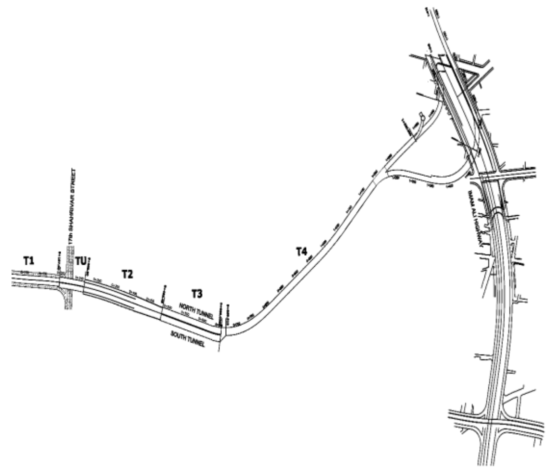


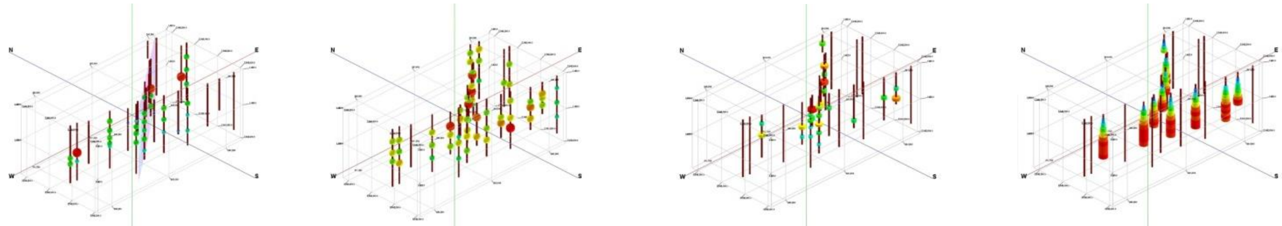
Fig 2 Plan of different divisions of Amirkabir project

Furthermore, according to the geological map of study area, formations of A and D as well as alluvial fan deposits have outcropped near this area.In order to achieve the project objectives, 12 boreholes with depth of 40 meters, 1 borehole with depth of 49 meters and 13 test pits have been drilled in the route of tunnel. The location of the boreholes and test pits are presented in Figure 3a.

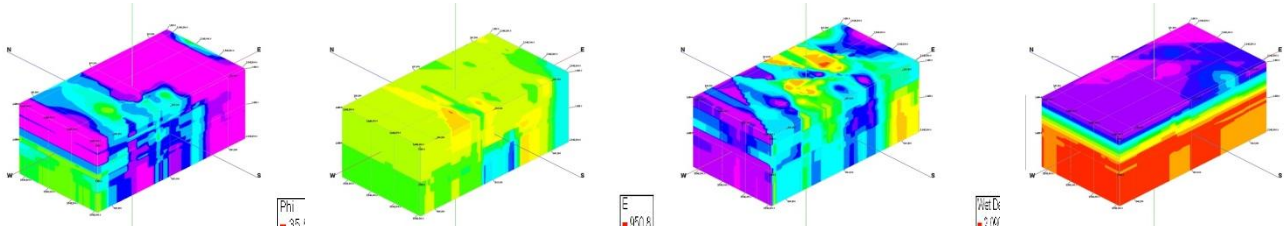
Standard Penetration tests (SPT) were done in all boreholes to investigate the strength and compressibility of the subsurface layers. Required samples were taken during the drilling and were sent to laboratory to perform different tests. Borehole logs have been prepared based on field observations during drillings, grain size analyses and classification of the samples.
According to the field and laboratory test results and site investigations, subsurface layers conditions are generally coarse grain soils and consist of very dense gravel and sand. The groundwater table is different in the boreholes, whereas it is lower than the depth that might be important to the project goals.

Uncertainty in the Soil Model of The Site

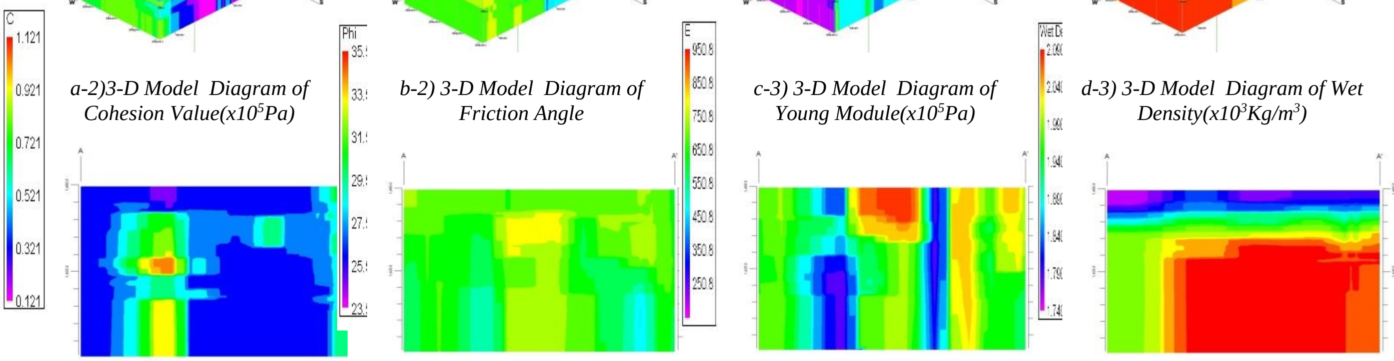
A range of in-situ and laboratory experiments including Standard Penetration Test (SPT), in-situ density,Pressuremeter test, permeability test (Lefrunc), in-situ shear test and plate load test at the location of the boreholes had been performed.



a-1)Variation in Cohesion Value of Boreholes(x10^{5}Pa)	*b-1)Variation in Friction Angle of Boreholes*	*c-1)Variation in Young Module of Boreholes(x10^{5}Pa)*	*d-1)Variation in Wet Density Value of Boreholes(x10^{3}Kg/m^3)*



a-2)3-D Model Diagram of Cohesion Value(x10^{5}Pa)	*b-2) 3-D Model Diagram of Friction Angle*	*c-3) 3-D Model Diagram of Young Module(x10^{5}Pa)*	*d-3) 3-D Model Diagram of Wet Density(x10^{3}Kg/m^3)*



a-2)Cross Section through Tunnel Axis o indicating variation of Cohesion Value(x10^{5}Pa)	*b-2) Cross Section through Tunnel Axis indicating variation of Friction Angle*	*c-3) Cross Section through Tunnel Axis indicating variation of Young Module(x10^{5}Pa)*	*d-3) Cross Section through Tunnel Axis indicating variation of Wet Density(x10^{3}Kg/m^3)*

Fig 3 Variation in soil characteristic of the site area

Considering the field and laboratory test results, on the whole, the soil of the area is composed of dense sandy gravels and dense sand, which both contains silt and clay (GC, GM, SC and SM). Sometimes these materials contain 5 to 50 percent of fine-grained soils. Moreover, silty and clayey inter layers have been observed rarely. Figure 3 illustrates the variation of four different soil parameters visualizing in 3D and 2D diagrams.

<u>Excavation Methods</u>

Construction has been performed by different methods i.e., Underground excavation, Cut and Cover and Top/Down methods in different sections of the project depending on the soil overburden and mechanical properties of the soil.At the locations with minimum required soil overburden, underground excavation method (NATM) has been performed (Figure 4). Rest of project has been constructed by either Cut & Cover method (where there is no limitation for blocking the road; Figure 5) or Top/Down method (where there is limitation for blocking the road for some time and construction shall be performed with minimum blocking time of the road; Figure 6).

In Cut & cover method stabilization of the trenches has been performed by either Nailing (Figure 7) or Bored piling method. Deformations and settlements have been monitored during and after construction in order to avoid unpredictable deformations and as a result any possiblefailure.

Fig 4 NATM excavation method in T4 section

Fig 5 Cut & Cover method in T2 section

Fig 6 Top/Down method inT4 section

Fig 7 Nailing at TU Portal area

Instrumentation

Large numbers of surface settlement markers were installed to measureground settlements during excavation. Arrays of surfacesettlement markers were arranged approximately at intervals of30 m along the tunnel alignment. The Wild NA2 Automatic Engineers' Level was used for the measurement. It permits direct readings to 0.1 mm and estimated readings to 0.01 mm.

GENERAL APPROACH TO MANAGE UNCERTAINTIES OF THE TUNNEL: PART T4 OF THE PROJECT

In this project, a probabilistic hypothetical elasticity modulus (PHEM) approach has been used to evaluate the uncertainty in the initial lining design of NATM tunnels in soft ground.Figure 1 shows the main elements and flow of the proposed approach, which used to reliable design of tunnels.The approach consists 4 principal elements (Fig 8):

1. 3D modeling of tunnel using time dependent sprayed shotcrete
2. 2D modeling of tunnel using Time dependent hypothetical elasticity modulus
3. Stochastic model of the system
4. Monitoring

The stress redistribution and the deformations occurring during tunnel face advance can be more properly simulated only if 3D numerical models are applied.However, in many cases, especially when reliability analysis is considered, performing of a 3D model in conjunction with a stochastic model to simulate the uncertainty of system is time consuming and often impracticable.

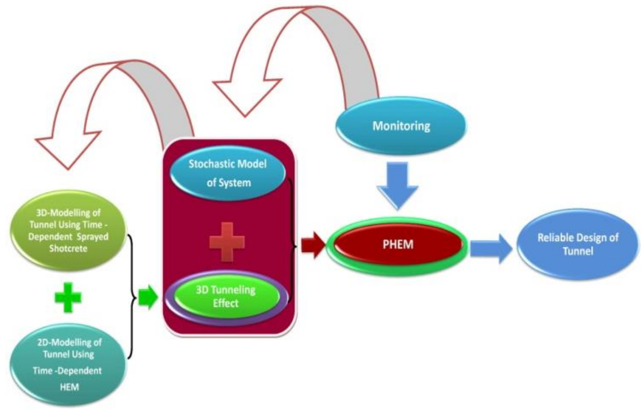


Fig 8 Concept of PHEM approach

3D tunneling effect can be derived from the comparison between 3D model with 2D model.According to (Chang 1994), a modified empirical exponential model, appropriate for both of the 2D and 3D time-dependent finite element models, was proposed for this research to model the changing of elasticity modulus of the sprayed concrete during the construction phases:

$$E_{ij} = 1.062 E_{28} / CR_j \cdot e^{-0.446/T_{i,j}^{0.7}} \quad (1)$$

where E_{ij} and T_{ij} (day) are the elasticity modulus and the average age of shotcrete of the part *i* of lining in phase *j* of excavation process, respectively and E_{28} is the 28-day elasticity modulus of concrete. In addition, CR_j ,is the calibration ratio derived from the comparison between 3D model with 2D models(this averagely was equal to 1.25 for T4 section).

The PHEM approach is based on limit state function, the type of limit state (i.e. Service Limit State, Strength Limit State, Extreme Limit State, or Fatigue Limit State) should be defined to characterize the applied loads. With regard to the case in this paper, performance of the initial lining of the tunnel has been considered. Accordingly, the loads of the service condition have been defined stochastically (Table 1).
A finite Element analysis was conducted using the ABAQUS

pre- and post-processing finite element program. Simulation of the NATM tunneling process was commenced with the selection of the tunnel geometry and the model geometry in two-dimensions. Plane strain analysis was used in the analysis. Amirkabir's soil was modeled using the undrained material properties with the Mohr-Coulomb failure or strength criterion. The probabilistic model of the soil was constructed based on in-situ and laboratory experiments mentioned before in Figure 3.

The water table is assumed to be 40m below the ground surface. Shotcrete used as a preliminary support measure in the tunnel has been modeled using elastic beam elements in the FEM analysis. In order to estimate the surface settlement, the Hypothetical Modulus of Elasticity (HME) soft lining approach(Karakus 2007, Karakus and Fowell 2003, John and Mattle 2003, Potter 1990), has been used in this research due to its flexibility when applied to multistage tunnel excavations.
Regarding the changes in the amount of overburden along the axis of the tunnel T4, two different geometries with different overburden (5m representing the sections with overburden less than 5m; and 10m for the sections with the overburden between 5m and 10m) with 120 m wide and 40 m high were used and were named A and B(Fig. 9).

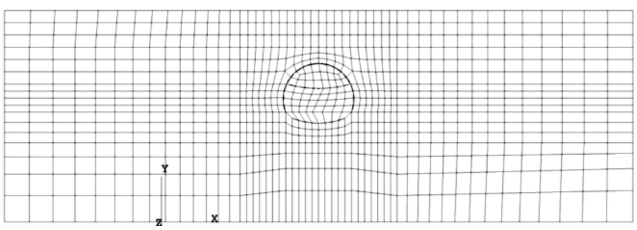


Fig 9 Adoptedfinite element model

Based on conceptual design of the tunnel (Fig 10), the detailed analysis procedures employed during this parametric sequential excavation model (PSEM) are as follows:

Geostatic step: Introducing the initial stress state to reach equilibrium before tunnel excavation begins. The beam elements representing the lining were deactivated, as there was no lining at the beginning of the analysis.

1st cycle excavation step: Excavation of the top heading was achieved using the model change options in ABAQUS.
Meanwhile, the lining elements for the top heading with lower elasticity modulus were activated. A parametric HEM-value (TOPHEM1) was used for the Young Modulus of lining.

1st cycle lining step: The stiffness of the beam element for the top heading, i.e. the HME value, was increased to TOPHEM2, which is the assumed time dependent elasticity modulus of the lining.

2nd cycle excavation step: The continuum elements in the left invert were removed and the beam elements with an LEFTHEM1 value for sidewall were activated.

2nd cycle lining: The HME value for the lining on the left periphery and top heading increased to LEFTHEM2 and TOPHEM3, respectively.

3rd cycle excavation step: The solid elements representing the right bench were removed and the beam elements representing the lining with an RIGHTHEM1 value for the wall were activated.

3rd cycle lining step: The HEM value for the lining for the right bench, left bench and top heading increased to RIGHTHEM2, LEFTHEM3 and TOPHEM4, respectively.
4th cycle excavation step: The continuum elements in the invert were removed. This is followed by the activation of the beam elements representing the lining with INVERTHEM1 value for the invert.

4th cycle lining step: Increasing the value of HME for invert, the right bench, left bench and top heading to INVERTHEM2, RIGHTHEM3, LEFTHEM4 and TOPHEM5, respectively and simulation was completed.

Based on a MATLAB(Matlab 2010) interface program, 1000 Latin Hypercube simulations were performed on each of the non-circular surface to determine the probabilistic limit state functionof ABAQUS-based finite element model(ABAQUS 2010) which was described above. Providing the probabilistic properties of the parameters, full characterization of the system and the other related information are described inTables2, 3.The existing road and buildings over the tunnel considered by two different linear distribution loads with the parametric value of ROADLOAD and BUILLOAD, respectively.

Table 2 Probabilistic parameters of the HEMs

Parameter	$T_{i,j}$ Average (h)	$T_{i,j}$ Lower Band(h)	$T_{i,j}$ Upper Band(h)	Distribution
TOPHEM1	6	5	7	Uniform
TOPHEM2	30	27	33	Uniform
TOPHEM3	87	80	95	Uniform
TOPHEM4	129	115	140	Uniform
TOPHEM5	215	195	235	Uniform
LEFTHEM1	6	5	7	Uniform
LEFTHEM2	30	27	33	Uniform
LEFTHEM3	87	80	95	Uniform
LEFTHEM4	129	115	140	Uniform
RIGHTHEM1	6	5	7	Uniform
RIGHTHEM2	30	27	33	Uniform
RIGHTHEM3	87	80	95	Uniform
INVERTHEM1	6	5	7	Uniform
INVERTHEM2	30	27	33	Uniform

The probabilistic limit state function was defined as below:

$$\begin{aligned} &f(X) \geq 0 \rightarrow Safe \\ &f(X) < 0 \rightarrow Failure \\ &X = [x_1, x_2, \ldots, x_N] \end{aligned} \quad (2)$$

Where X is the vector of model input and N is the number of

Table 3 Probabilistic parameters of the system

Parameter	Symbol	Mean	STD	Lower Bound	Upper Bound	Distribution	Unit	Variable' s Name
Soil Parameters Distribution								
Cohesion	C_{soil}	3.12E4	6.21E3	2.7e4	1.19E5	logN	Pa	CSOIL
Friction angle	φ_{soil}	32.45	1.72	29	35.3	N	Degree	PHISOIL
Young's modulus	E_{soil}	8.41E+7	2.90E+7	1.68e7	9.66e7	N	Pa	ESOIL
Poisson ratio	υ_{soil}	0.3	0.03	0.285	0.315	Beta	-	POSOIL
Density	γ_{soil}	1960	120	1720	2090	N	Kg/m^3	DENSOIL
Lining Parameters Distribution								
Density	γ_{con}	2400	240			N	Kg/m^3	DENCON
Young's modulus	$E_{28}=4.7E6\times\sqrt{f'_c}$						Pa	ELBEAM
28-day Compressive Strength	f'_c	2.5E7	4E+6	1.4E7		N	Pa	COMPST
Poisson ratio	υ_{con}	0.2	0.02	0.18	0.22	Beta	-	POIBEAM
Thickness	t	0.27	0.03	0.24	0.30	U	m	TBEAM
Loading Parameters Distribution								
Road Load	LL	30000	7500			N	Pa	ROADLOAD
Building Load	DL	20000	5000			N	Pa	BUILLOAD

random variables. For the Service Limit State, f is characterized as(FHWA 2001, Hung et al. 2009):

$$y = f(X) = \delta_n - \delta_i \qquad (3)$$

where δ_i is the estimated displacement and δ_n is tolerable displacement established by designer.

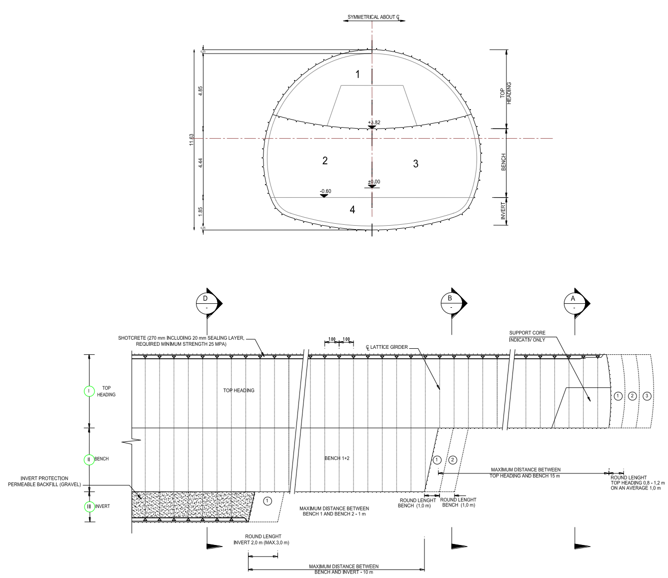


Fig 10 NATM Excavation Stages

Latin Hyper Cube Simulation (LHCS) Results

Performing 1000 LHCS for each model, a set of stratified probabilistic distribution function (PDFs) of maximum surface settlement was derived for each.

The statistical results indicated that the settlements of the model A were in the range between 19mm and 51mm, with the mean-value and standard deviation(STD) of 31mm and 5mm, respectively, whereas the mean-value and STD of the outputs of model B were 41mm and 5mm, respectively.

Meanwhile, the maximum of settlements reached a pick-value of 58mm; and its minimum value was 31mm.

Stochastic Results

As the results of Monte Carlo simulation (MCS), Figure 11 shows the surface plots of 5 principle variables of the system which were compared two by two versus maximum transversal settlement (MINDIS) of two different models.

Regarding the changing trends of variables versus the output, it can be seen that the model is more sensitive to the variable of the soil as well as active loading, excepting the load of building, than the factors depending to the structure.

More investigation in Monte Carlo simulation, not included in this paper, shows that the proposed sequential excavation method is numerically certain enough throughout the length of the tunnel in order to limit the surface settlements induced.

Monitoring Feedbacks

Based on the measurement of settlement pins installed on the pavement of road above the tunnel, the monitored transversal settlements of surface road during the construction phase are illustrated in Figure 13.

Regarding the measured settlement, it is crucial to import that none of the cases surveyed have indicated serviceability failure. This emphasizes the fact that the construction method was safe enough, having adopted by the MCS results.

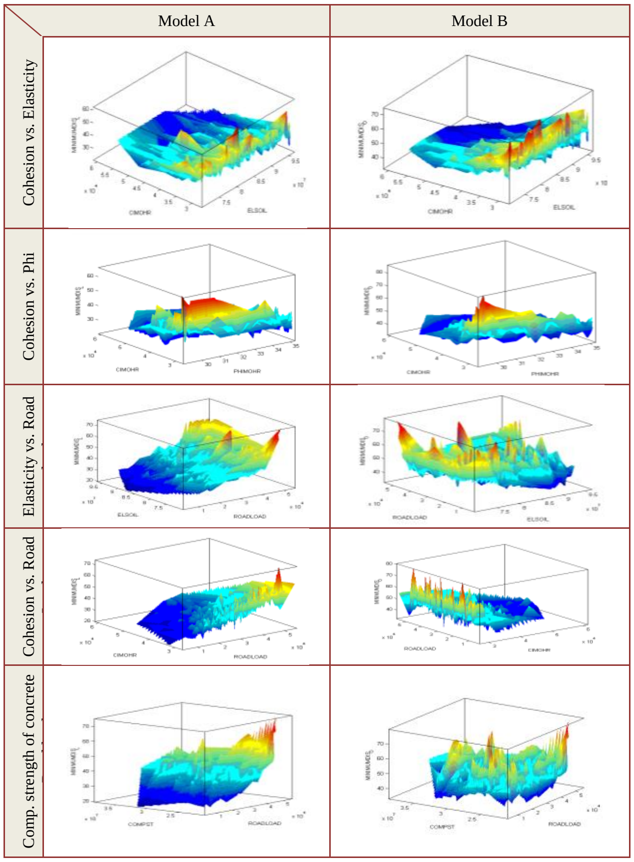


Figure 11 Surface plots of 5 principle variables of the system based on Monte Carlo simulation output

CONCLUSION

The work reported in this paper specifically dealt with Amirkabir highway tunnel which is one of the important projects excavating below one of the highest traffic region of Tehran, including the difficulty of excavating through a heterogeneous sedimentary basin mainly composed of recent alluvial.

Construction has been performed by different methods i.e., Underground excavation, Cut and Cover and Top/Down methods in different sections of the project. Deformations and settlements have been monitored during and after construction in order to avoid unpredictable deformations and as a result any possible failure. Using different methods of excavation to avoid worse case settlement in different part, a probabilistic approach, Monte Carlo simulation algorithm (Latin Hyper Cube sampling), has been employed to evaluate the uncertainty in lining design of the part T4 of the project.

The MCS results of section T4 showed that regarding uncertainties related to the system, the model was more sensitive to the variable of the soil as well as active loading than the factors depending to the structure and also advance rate.

Comparing monitoring data with stochastic outcomes of the model demonstrated that the method used in this research to simulate the uncertainty of the system gave real judgment on the consequences of the excavation phase of the project. On the whole, turning to a probabilistic method in design could help in predicting the excavation-induced transversal settlement, having treated uncertainties related to the excavation rate and soil properties.

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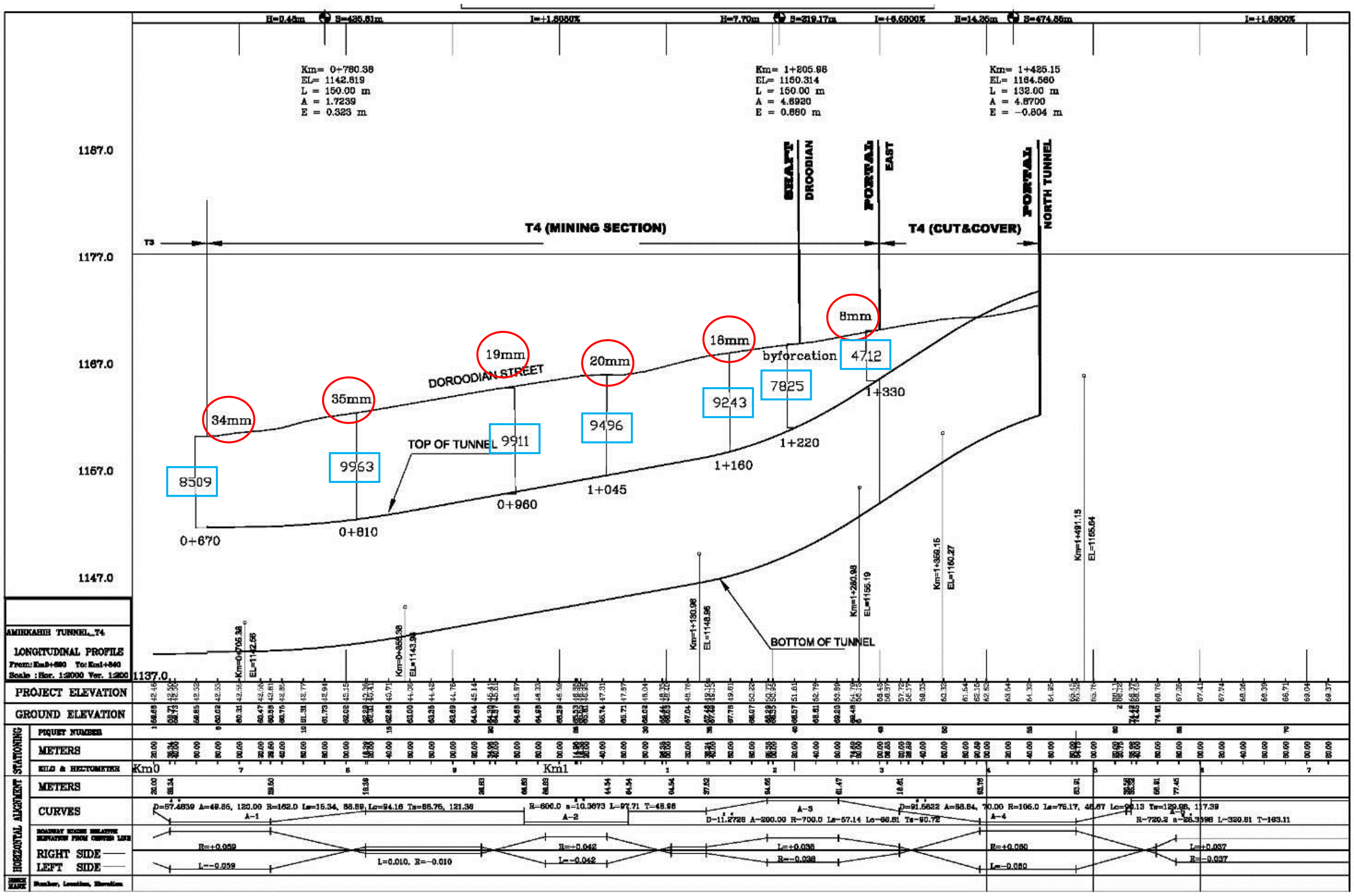

Figure 13 North tunnel longitudinal profile (numbers marked by red circles and blue rectangulars indicate the monitored transversal settlements of surface road and the values of overburden in each station, respectively)